Size effect and the quadratic temperature dependence of the transverse magnetoresistivity in "size-effect" tungsten single crystals

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Size effect and the quadratic temperature dependence of the transverse magnetoresistivity in "size-effect" tungsten single crystals

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Abstract. The transverse magnetoresistivity of pure tungsten single crystals with a residual resistivity ratio $\rho_{293K}/\rho_{4.2K}$ of about 75000 was measured from 4.2 to 20 K and in magnetic fields of up to 15 T. The size effect, i.e. the linear dependence of the magnetoconductivity on the inverse cross sample dimensions, was studied in detail at high fields. We show that the size effect can be used for the separation of the contributions from the electron-surface and the electron-phonon scattering mechanisms to the full conductivity. We demonstrate that the electron-phonon scattering leads to the exponential temperature dependence of the conductivity, and the interference between the electron-phonon and the electron-surface processes leads to a new scattering mechanism "electron-phonon-surface" with a quadratic temperature dependence of the magnetoconductivity.

1. Introduction

The mean free path of the conduction electrons reaches a few millimeters in pure metal single crystals at low temperatures and becomes comparable with the transverse sample dimension. This leads to the size effect in the electro- [1] and magnetoresistivity [2] of pure metals, i.e. to the linear dependence of the electro- and magnetoresistivity on the inverse cross sample dimensions. It was suggested in Ref. [2] that this phenomenon can be used for the separation of the surface and the volume contributions to the total magnetoconductivity of the sample.

The aim of this paper is to study the size effect in the transverse magnetoresistivity (magnetoconductivity) of pure tungsten single crystals, to separate the contributions to the total magnetoresistivity of the interactions of the conduction electrons with the sample surface and in the crystal volume and to analyze their temperature dependence.

2. Experimental

Tungsten single crystals with residual resistivity ratios of up to 75000 were used. The temperature dependence of the transverse magnetoresistivity ρ_{xx} was measured at temperatures from 4.2 to 20 K and in magnetic fields of up to 15 T. To simplify the interpretation of the data, the results are presented in terms of the magnetoconductivity $\sigma_{xx} \approx \rho_{xx}^{-1}$ [3].

3. Results

According to Ref. [2], the high-field magnetoconductivity σ_{xx} of pure compensated metals can be represented as follows

$$\sigma_{xx} = (2r_H/d)\cdot\sigma_{xx}^{sur} + \sigma_{xx}^{vol}, \quad (1)$$

where r_H is the Larmor radius, d is the cross sample dimension, and σ_{xx}^{sur} and σ_{xx}^{vol} are the surface and the volume magnetoconductivities, respectively.

To study the size effect, a few samples with different dimensions were prepared from a pure tungsten ingot. Two types of samples were cut. For the first, the lateral faces were the crystallographic (110) planes, and for the second the (100) planes. The magnetic field was applied along <100> in both cases. Then the magnetoresistivity (magnetoconductivity) was measured. The results for a magnetic field of 10 T at T=5K are shown in Fig. 1, which demonstrates that the size effect in the magnetoconductivity, i.e. a linear dependence of σ_{xx} on the inverse dimension d^{-1}, really occurs. It should be noted, that the slope of the curve for samples with «specular» faces (110) is bigger than that for samples with «diffuse» faces (100).

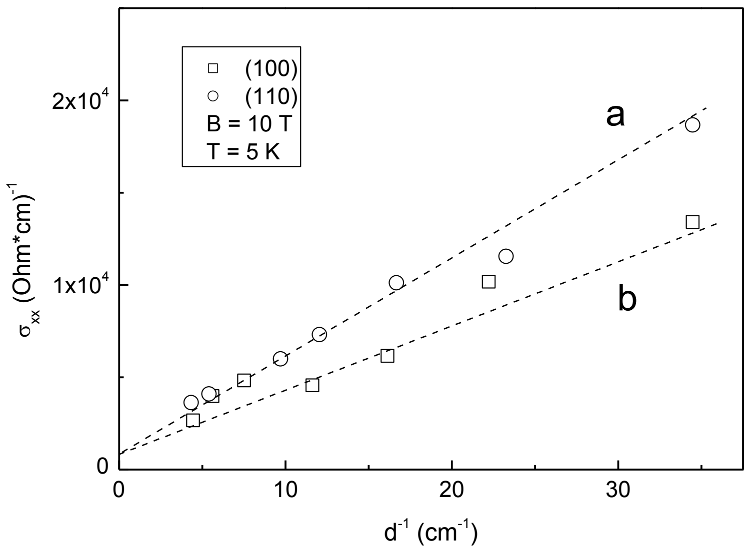

Figure 1. Size dependence of $\sigma_{xx} = f(d^{-1})$ for tungsten in a field of 10 T at T = 5 K. (a) samples with (100) faces; (b) samples with (100) faces.

Using extrapolation to a “massive” sample with infinite dimension ($d^{-1} \rightarrow 0$) (Fig. 1), the volume magnetoconductivities σ_{xx}^{vol} for both sample types are obtained. $\sigma_{xx}^{vol\ (110)} \approx (1.30\pm0.25)\cdot10^3$ $(\mathrm{Ohm\cdot cm})^{-1}$ for samples with (110) faces and $\sigma_{xx}^{vol\ (100)} \approx (1.35\pm0.25)\cdot10^3$ $(\mathrm{Ohm\cdot cm})^{-1}$ for samples with (100) faces. The magnitudes of the volume conductivities $\sigma_{xx}^{vol\ (110)}$ and $\sigma_{xx}^{vol\ (100)}$ are approximately the same, because the size effect should not occur in “massive” samples with infinite dimensions.

Using the data of Fig. 1 and expression (1) the surface conductivities $\sigma_{xx}^{sur\ (110)}$ and $\sigma_{xx}^{sur\ (100)}$ have been estimated. For example, the surface conductivities for samples with d = 0.1 cm are $\sigma_{xx}^{sur\ (110)} \approx 2.9\cdot10^6$ $(\mathrm{Ohm\cdot cm})^{-1}$ for samples with “specular” faces (110) and $\sigma_{xx}^{sur\ (100)} \approx 1.9\cdot10^6$ $(\mathrm{Ohm\cdot cm})^{-1}$ for samples with “diffuse” faces (100). Thus, we demonstrate that the observed size effect in the magnetoconductivity can be used for the separation of the volume and surface contributions to the total magnetoresistivity of such pure metal single crystals.

It is quite interesting to analyze the temperature dependences of σ_{xx}^{vol} (T) and σ_{xx}^{sur} (T). Therefore, the surface and the volume contributions to the magnetoconductivity were separated for both sample groups from 5 to 15 K and the temperature dependences σ_{xx}^{vol} (T) and σ_{xx}^{sur} (T) studied.
The analysis of σ_{xx}^{vol} (T) shows that the volume conductivity σ_{xx}^{vol} is proportional to an exponent. It is known from Ref. [4] that intersheet electron–phonon scattering is one of the main scattering mechanisms of the conduction electrons in tungsten single crystals, which can lead to an exponential temperature dependence of the high-field magnetoconductivity. A comparison of our results with those of Ref. [4] allows us to conclude that the high-field magnetoconductivity $\sigma_{xx}^{vol\ (100)}$ at low temperature has an exponential temperature dependence and is caused by intersheet electron-phonon scattering of the conduction electrons.
According to Ref. [1], the interaction of the conduction electrons with the sample surface of pure tungsten can lead to a quadratic temperature dependence of the electroresistivity $\rho \sim T^2$ due to the interference scattering mechanism "electron-phonon-surface". Since such a behavior is observed in pure tungsten and under conditions of the size effect without magnetic field, the issue of the type of temperature dependence of the surface magnetoconductivity σ_{xx}^{sur} in high magnetic field arises.
Fig. 2 shows the temperature dependence of $\sigma_{xx}^{sur\ (100)}$ for a tungsten sample with cross dimension d=0.1 cm and with (100) faces in a field of 10 T. It is linear in the coordinate system of $\sigma_{xx}^{sur\ (100)} = f(T^2)$, i.e. the surface conductivity $\sigma_{xx}^{sur\ (100)} \sim T^2$. Taking this result into account and the data of Ref. [1], we conclude that the quadratic temperature dependence of the surface magnetoconductivity $\sigma_{xx}^{sur\ (100)}$ at low temperatures and high magnetic fields is caused by the interference scattering mechanism "electron-phonon-surface".

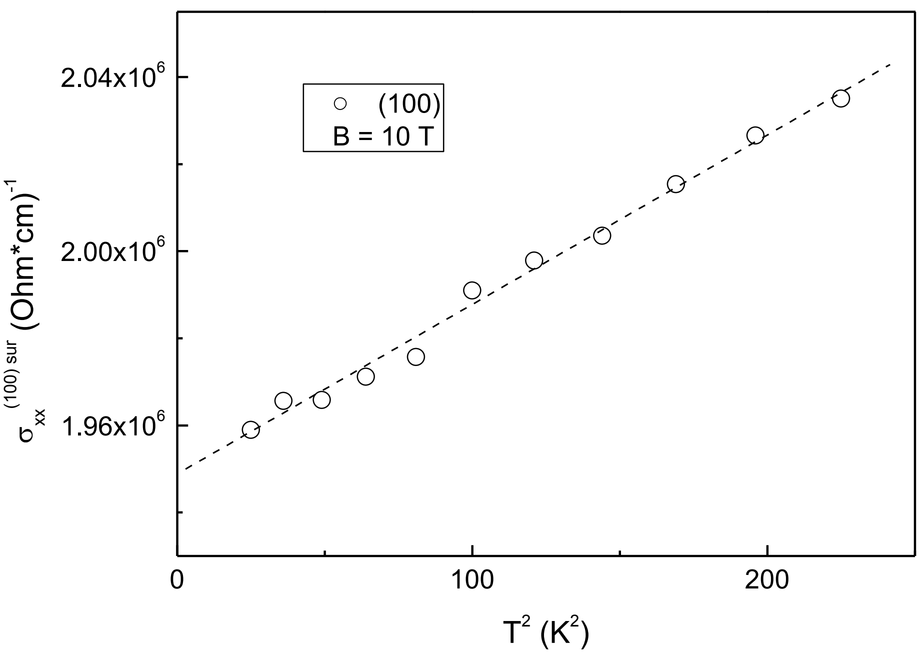

Figure 2. Temperature dependence of the surface conductivity $\sigma_{xx}^{sur\ (100)} = f(T^2)$ for a tungsten sample with d=0.1 cm and (100) faces in a field of 10 T.

4. Conclusions

1. We show that the size effect can be used for the separation of the volume σ_{xx}^{vol} and the surface σ_{xx}^{sur} magnetoconductivities due to the electron-phonon and the electron-surface scattering mechanisms of the conduction electrons for pure tungsten single crystals.
2. We analyzed the temperature dependences of the volume σ_{xx}^{vol} and the surface σ_{xx}^{sur} magnetoconductivities and demonstrate that electron-phonon scattering leads to an exponential temperature dependence of σ_{xx}^{vol}, and further that the interference between the electron-phonon and the electron-surface processes leads to the scattering mechanism “electron-phonon-surface” with a quadratic temperature dependence of σ_{xx}^{sur}.

5. Acknowledgements

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